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The general objectives of this research are to systematically investigate the interaction of electromagnetic radiation in the far infrared range with the charge carriers in semiconductor heterojunction superlattice structures. Experiments are performed on both the lattice-matched $GaAs/Al_xGa_{1-x}As/GaAs$ heterojunction material structures and the strained-layer material of $In_xGa_{1-x}As/GaAs$ heterostructure. In the fomer case, new electronic processes are discovered and their possible detector application is explored. In the latter case, the energy level structure is determined and the carrier dynamics are studied using the submillimeter wave spectroscopy.

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Submillimeter Wave Spectroscopy of Heterojunction

Superlattices: A Final Technical Report

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Abstract

This is the final technical report describing the research carried out during the period from September 30, 1988, to September 29, 1991, under the Air Force Office of Scientific Research Contract No. 88-0248. Briefly discussed are the results from experiments on the interaction of submillimeter electro-magnetic radiation with the charge carriers in semiconductor heterojunction thin film structures of lattice matched $GaAs/Al_xGa_{1-x}As$ and strained-layers of $In_xGa_{1-x}As/GaAs$.

I. Introduction

The general objectives of this research are to systematically investigate the interaction of electromagnetic radiation in the far infrared range with the charge carriers in semiconductor heterojunction superlattice structures. Experiments are performed on both the lattice-matched $GaAs/Al_xGa_{1-x}As$ heterojunction material structures and the strained-layer material of $In_xGa_{1-x}As/GaAs$ heterostructure. In the former case, new electronic processes are discovered and their possible detector application is explored. In the latter case, the energy level structure is determined and the carrier dynamics are studied using the submillimeter wave spectroscopy.

II. Accomplishments

1. Landau level diode and its use as a tunable submillimeter wave detector.

We have succeeded in the fabrication of a new device, which we called the Landau level diode. It is based on the quantum physics properties of the two-dimensional electron gas (2DEG) realized in GaAs/$Al_xGa_{1-x}As$ heterostructures in the integral quantized Hall effect regime. The device is a 2D analogue of the p-n junction and Fig. 1 is an illustration of the energy band diagram. The conduction

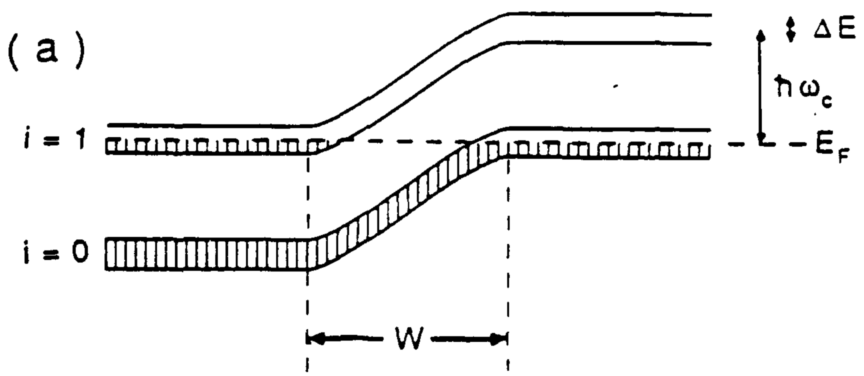

Fig. 1. Energy diagram of a Landau level diode. In equilibrium, E_F crosses between the i = 0 and the i = 1 Landau level.

and valence bands are now two partially filled, adjacent Landau levels. The energy gap, which is the gap between them, can be tuned continuously by the applied magnetic field. In our device, an Al gate is fabricated over part of the GaAs/$Al_xGa_{1-x}As$ heterostructures. The application of a gate voltage changes the 2DEG density underneath the gated portion of the device and creates the density discontinuity at the gate edge, which is the origin of the depletion region in the

device. The device has the I-V characteristic of a backward diode.

We have investigated the photoresponse of the diode in the far infrared and observed the photovoltaic effect. It results from the generation of electron-hole pairs by cyclotron resonance between the Landau levels and the subsequent drift of these free carriers in the built-in electric field of the diode. The device is a wavelength tunable far infrared photodetector. The quantum efficiency η, the detectivity, $D\lambda^*$, and the responsivity, $R\lambda$, of the present device are: $\eta = 5.2\%$, $D\lambda^* \approx 1.8 \times 10^{11} cmHz^{1/2}/W$ and $R\lambda = 0.1mA/W$. A change in design, which will increase the active device area from 0.003% of the illuminated area in our present device to ~5%, is expected to increase $R\lambda$ to ~0.02 A/W. $D\lambda^*$ can also exceed $10^{12} cmHz^{1/2}/W$ by an increase in the detector resistance.

2. Far infrared and capacitance studies of GaAs/AlGaAs lateral-surface-superlattices created by grid gate structures.

We have, in collaboration with a group at MIT headed by Professors D. Antoniadis and H. Smith, started a program to systematically investigate the far infrared response of the two-dimensional electron gas (2DEG) in the presence of a periodic surface potential. The program combines the MIT expertise on nanolithography technology and ours on low temperature far infrared spectroscopy to explore the new electron physics in both the classical and the quantal limit.

We have made far-infrared (FIR) transmission measurement on grid-gate lateral surface-superlattice on GaAs/AlGaAs heterostructures. The Ti/Au grid-gate has a 2000Å period and a 850Å linewidth. The density of the electron gas

at the GaAs/AlGaAs interface is characterized with magneto-capacitance measurements, which show that, while the gated regions are totally depleted at a threshold gate voltage V_T, the electron concentration in the ungated regions is affected only slightly by the applied gate voltage V_g. The magneto-transmission spectra, obtained with optically pumped FIR lasers, show different features before and after the gated regions are totally depleted. Before the gated regions are totally depleted, two resonance dips are observed with four different lines of photon energies E_υ between 6.5 and 8.2meV. One occurs at a B close to the cyclotron resonance (CR) position B_{CR} of the homogeneous 2D electron gas, and the other occurs at an unexpected higher B. When E_υ is outside the above energy range, only the former is observable. At $V_g < V_T$, after the gated regions are totally depleted, only one resonance is observed a B smaller than B_{CR}. This resonance is attributed to electric dipole transitions between energy levels resulting from the confinement of the electrons into quasi zero-dimensional quantum dots. The shifted resonance positions are in good agreement with our theoretical calculation using a 2D harmonic confining potential.

3. Cyclotron resonance of two dimensional holes in strained-layer GaAs/$InGa_{0.20}As_{0.80}$/GaAs quantum well structures

The $In_xGa_{1-x}As$/GaAs strained-layer quantum well structure is one of the favored materials for high speed complimentary logic devices and low threshold, long wavelength semiconductor laser applications. The biaxial compressive strain due to the lattice mismatch in the $In_xGa_{1-x}As$ layer removes the valence band (VB) degeneracy at the Γ point. As a result, the heavy hole (HH) band (i.e., the J

$= 3/2$, $m_j = \pm 3/2$ band) becomes the uppermost VB and is expected to have light in-plane hole mass. The high-mobility hole transport in the VB and the reduced threshold current density for pumping semiconductor laser are direct consequence of this light in-plane hole mass. The VB structure of strained $In_xGa_{1-x}As$ layer has been studied indirectly by many techniques including the interband optical transition and transport measurements. Our work is the first systematic study on such material systems using a direct cyclotron resonance measurement in the far-infrared.

We have studied this strain-split HH band in the energy range of about 1 meV to 20 meV above the valence band edge by tuning the two-dimensional hole gas density from 5.4 x 10^{10} to 1.65 x $10^{12}/cm^2$. By measuring the effective mass of the two-dimensional holes, we show that the HH band can be described by a band edge mass m_o^* of $(0.120 \pm 0.005)m_e$ and a non-parabolicity factor. This m_o^* uniquely characterizes the strained-layer $In_{0.20}Ga_{0.80}As$ valence band parameter, $1/(\gamma_1 + \gamma_2)$.

4. Conduction band offset in strained $Al_{.15}Ga_{0.85}As/In_{0.15}Ga_{0.085}$/As/GaAs quantum well structures.

The use of strained-layers has increased the flexibility of choosing consitituent materials and has expanded the number of useful heterostructures. By varying the composition of a heterostructure, the relative band line-up between two adjacent materials can be tailored and modified to the specific device application. One important parameter for designing such heterostructure devices is the condition (valence) band discontinuity $\Delta E_c(\Delta E_v)$ at the heterojunction interface.

We have made the first determination of ΔE_c in strained-layer $Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As/GaAs$ pseudomorphic structure. Schubnikov-de Hass cyclotron resonance experiments were carried out to independently determine the two-dimensional electron gas density and its effective mass for a series of samples with a range of spacer thickness from 30 to 100Å. Using a charge transfer model, ΔE_c at the $Al_{0.15}Ga_{0.15}As/In_{0.15}Ga_{0.85}As$ interface is found to be (255 ± 35) meV, which accounts for 76% of the band gap discontinuity.

5. Magneto-optics of the strained-layer $InAs_{0.15}Sb_{0.85}/InSb$ superlattice

The $InAs_xSb_{1-x}/InSb$ strained layer superlattice (SLS) is a new class of III-V material system for future infrared detector and focal plane array technology applications. The alternating biaxial compressive and tensil strain in the InSb and $InAs_xSb_{1-x}$ layers respectively modifies the band structure of the SLS such that its energy band line-up is type-II, (electrons and holes are confined in separated layers of the SLS). The long wavelength ($>=10\mu m$) optical response of the $InAs_xSb_{1-x}/InSb$ SLS is an example of the novel optical and transport properties of the type-II band line-up. This type-II band line-up has been inferred indirectly from optical absorption, photo-luminescence and the temperature dependence of the Schubnikov-de Hass measurements. Our work is the first direct evidence that the energy line-up of the $InAs_{0.15}Sb_{0.85}$ SLS is type-II by using cyclotron resonance technique.

We found that the in-plane effective masses of the two-dimensional hole gas are light, 0.034 and 0.054 m_e, in comparison to the heavy hole mass of 0.05 m_e at Γ in bulk InSb and must originate from the biaxially compressed InSb layer. As a

result, the InSb valence band edge is higher in energy than the $InAs_{0.15}Sb_{0.85}$ valence band edge. Since InSb has smaller band gap than the $InAs_{0.15}Sb_{0.85}$, our observation is direct evidence for a type-II line-up.

In addition, we have observed a spin resonance of holes in the hole CR-inactive sense of circular polarization from which we deduced an effective g-factor of 140.

III. Published reports of work supported by the contract

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J1. "Far infrared photovoltaic effect in a Landau level diode," C.T. Liu, B.E. Kane, D.C. Tsui, and G. Weimann, Appl. Phys. Lett. **55**, 162 (1989).

J2. "Linewidth anomaly of two-dimensional electron cyclotron resonance in the extreme quantum limit," C.T. Liu, P. Mensz, D.C. Tsui, and G. Weimann, Phys. Rev. **B40**, 1716 (1989).

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C1. "Far infrared red transmission measurement on grid gate GaAs/$Al_xGa_{1-x}As$ lateral surface superlattice structures," C.T. Liu, K. Nakamura, D.C. Tsui, K. Ismail, A.D. Antoniadis, H.I. Smith, Surf. Sci. **228**, 527 (1990).

C2. "A lateral-surface-superlattice structure on GaAs/AlGaAs for far infrared and magneto-capacitance measurements," K. Ismail, D.A. Antoniadis, H.I. Smith, C.T. Liu, K. Nakamura, and D.C. Tsui, J. Vac. Sci. Technol. **B7**, 2000 (1989).

C3. "Far infrared laser spectroscopy of two-dimensional holes in strained layer heterostructures and superlattices," S.Y. Lin, D.C. Tsui, J.F. Klem, L.R. Dawson, and E.D. Jones, Proc. of MRS Fall Meeting, Boston, 1990.

C4. "Magnetoresistance of two-dimensional electrons in a two-dimensional

lateral surface superlattice," C.T. Liu, D.C. Tsui, M. Santos, M. Shayegan, K. Ismail, D.A. Antoniadis, H.I. Smith, in Proc. of MRS Fall Meeting, Boston, 1990.

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